SUSTAINABLE SOIL MANAGEMENT

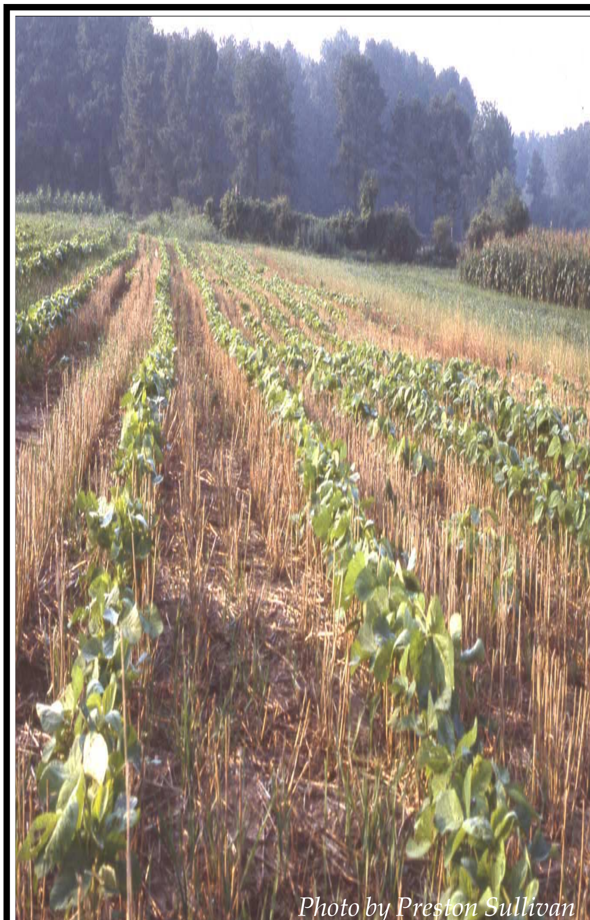
SOIL SYSTEMS GUIDE

1-800-346-9140
ATTRA
National Sustainable Agriculture Information Service
www.attra.ncat.org

Abstract: *This publication covers basic soil properties and management steps toward building and maintaining healthy soils. Part I deals with basic soil principles and provides an understanding of living soils and how they work. In this section you will find answers to why soil organisms and organic matter are important. Part II covers management steps to build soil quality on your farm. The last section looks at farmers who have successfully built up their soil. The publication concludes with a large resource section of other available information.*

By Preston Sullivan
NCAT Agriculture Specialist
May 2004

Table of Contents



Soybeans no-till planted into wheat stubble.

ATTRA is the national sustainable agriculture information service operated by the National Center for Appropriate Technology, through a grant from the Rural Business-Cooperative Service, U.S. Department of Agriculture. These organizations do not recommend or endorse products, companies, or individuals. NCAT has offices in Fayetteville, Arkansas (P.O. Box 3657, Fayetteville, AR 72702), Butte, Montana, and Davis, California.

Introduction

What are some features of good soil? Any farmer will tell you that a good soil:

- feels soft and crumbles easily
- drains well and warms up quickly in the spring
- does not crust after planting
- soaks up heavy rains with little runoff
- stores moisture for drought periods
- has few clods and no hardpan
- resists erosion and nutrient loss
- supports high populations of soil organisms
- has a rich, earthy smell
- does not require increasing inputs for high yields
- produces healthy, high-quality crops (1)

All these criteria indicate a soil that functions effectively today and will continue to produce crops long into the future. These characteristics can be created through management practices that optimize the processes found in native soils.

How does soil in its native condition function? How do forests and native grasslands produce plants and animals in the complete absence of fertilizer and tillage? Understanding the principles by which native soils function can help farmers develop and maintain productive and profitable soil both now and for future generations. The soil, the environment, and farm condition benefit when the soil's natural productivity is managed in a sustainable way. Reliance on purchased inputs declines year by year, while land value and income potential increase. Some of the things we spend money on can be done by the natural process itself for little or nothing. Good soil management produces crops and animals that are healthier, less susceptible to disease, and more productive. To understand this better, let's start with the basics.

> Sustainable: capable of being maintained at length without interruption, weakening, or losing in power or quality.

The Living Soil: Texture and Structure

Soils are made up of four basic components: minerals, air, water, and organic matter. In most soils, minerals represent around 45% of the total volume, water and air about 25% each, and organic matter from 2% to 5%. The mineral portion consists of three distinct particle sizes classified as sand, silt, or clay. Sand is the largest particle that can be considered soil.

Sand is largely the mineral quartz, though other minerals are also present. Quartz contains no plant nutrients, and sand cannot hold nutrients—they leach out easily with rainfall. Silt particles are much smaller than sand, but like sand, silt is mostly quartz. The smallest of all the soil particles is clay. Clays are quite different from sand or silt, and most types of clay contain appreciable amounts of plant nutrients. Clay has a large surface area resulting from the plate-like shape of the individual particles. Sandy soils are less productive than silts, while soils containing clay are the most productive and use fertilizers most effectively.

Soil texture refers to the relative proportions of sand, silt, and clay. A loam soil contains these three types of soil particles in roughly equal proportions. A sandy loam is a mixture containing a larger amount of sand and a smaller amount of clay, while a clay loam contains a larger amount of clay and a smaller amount of sand. These and other texture designations are listed in Table 1.

Another soil characteristic—soil structure—is distinct from soil texture. *Structure* refers to the clumping together or "aggregation" of sand, silt, and clay particles into larger secondary clusters.

Table 1. Soil texture designations ranging from coarse to fine.

	Texture Designation
Coarse-textured	Sand
	Loamy sand
	Sandy loam
	Fine sandy loam
	Loam
	Silty loam
	Silt
	Silty clay loam
	Clay loam
Fine-textured	Clay

If you grab a handful of soil, good structure is apparent when the soil crumbles easily in your hand. This is an indication that the sand, silt, and clay particles are aggregated into granules or crumbs.

Both texture and structure determine pore space for air and water circulation, erosion resistance, looseness, ease of tillage, and root penetration. While texture is related to the minerals in the soil and does not change with agricultural activities, structure can be improved or destroyed readily by choice and timing of farm practices.

The Living Soil: The Importance of Soil Organisms

An acre of living topsoil contains approximately 900 pounds of earthworms, 2,400 pounds of fungi, 1,500 pounds of bacteria, 133 pounds of protozoa, 890 pounds of arthropods and algae, and even small mammals in some cases (2). Therefore, the soil can be viewed as a living community rather than an inert body. Soil organic matter also contains dead organisms, plant matter, and other organic materials in various phases of decomposition. Humus, the dark-colored organic material in the final stages of decomposition, is relatively stable. Both organic matter and humus serve as reservoirs of plant nutrients; they also help to build soil structure and provide other benefits.

The type of healthy living soil required to support humans now and far into the future will be balanced in nutrients and high in humus, with a broad diversity of soil organisms. It will produce healthy plants with minimal weed, disease, and insect pressure. To accomplish this, we need to work *with* the natural processes and optimize their functions to sustain our farms.

Considering the natural landscape, you might wonder how native prairies and forests function in the absence of tillage and fertilizers. These soils are tilled by soil organisms, not by machinery. They are fertilized too, but the fertility is used again and again and never leaves the site. Native soils are covered with a layer of plant litter and/or growing plants throughout the year. Beneath the surface litter, a rich complexity of soil organisms decompose plant residue and dead roots, then release their stored nutrients slowly over time. In fact, topsoil is the most biologically diverse part of the earth (3). Soil-dwelling organisms release bound-up minerals, converting them into plant-available forms that are then taken up by the plants growing on the site. The organisms recycle nutrients again and again with the death and decay of each new generation of plants.

There are many different types of creatures that live on or in the topsoil. Each has a role to play. These organisms will work for the farmer's benefit if we simply manage for their survival. Consequently, we may refer to them as soil livestock. While a great variety of organisms contribute to soil fertility, earthworms, arthropods, and the various microorganisms merit particular attention.

Earthworms

Earthworm burrows enhance water infiltration and soil aeration. Fields that are "tilled" by earthworm tunneling can absorb water at a rate 4 to 10 times that of fields lacking worm tunnels (4). This reduces water runoff, recharges groundwater, and helps store more soil water for dry spells. Vertical earthworm burrows pipe air deeper into the soil, stimulating microbial nutrient cycling at those deeper levels. When earthworms are present in high numbers, the tillage provided by their burrows can replace some expensive tillage work done by machinery.

Figure 1. The soil is teeming with organisms that cycle nutrients from soil to plant and back again.

Worms eat dead plant material left on top of the soil and redistribute the organic matter and nutrients throughout the topsoil layer. Nutrient-rich organic compounds line their tunnels, which may remain in place for years if not disturbed. During droughts these tunnels allow for deep plant root penetration into subsoil regions of higher moisture content. In addition to organic matter, worms also consume soil and soil microbes. The soil clusters they expel from their digestive tracts are known as *worm casts* or *castings*. These range from the size of a mustard seed to that of a sorghum seed, depending on the size of the worm.

The soluble nutrient content of worm casts is considerably higher than that of the original soil (see Table 2). A good population of earthworms can process 20,000 pounds of topsoil per year—with turnover rates as high as 200 tons per acre having been reported in some exceptional cases (5). Earthworms also secrete a plant growth stimulant. Reported increases in plant growth following earthworm activity may be partially attributed to this substance, not just to improved soil quality.

Table 2. Selected nutrient analyses of worm casts compared to those of the surrounding soil.

Nutrient	Worm casts	Soil
	Lbs/ac	Lbs/ac
Carbon	171,000	78,500
Nitrogen	10,720	7,000
Phosphorus	280	40
Potassium	900	140

From Graff (6). Soil had 4% organic matter.

Earthworms thrive where there is no tillage. Generally, the less tillage the better, and the shallower the tillage the better. Worm numbers can be reduced by as much as 90% by deep and frequent tillage (7). Tillage reduces earthworm populations by drying the soil, burying the plant residue they feed on, and making the soil more likely to freeze. Tillage also destroys vertical worm burrows and can kill and cut up the worms themselves. Worms are dormant in the hot part of the summer and in the cold of winter. Young worms emerge in spring and fall—they are most active just when farmers are likely to be tilling the soil. Table 3 shows the effect of tillage and cropping practices on earthworm numbers.

Table 3. Effect of crop management on earthworm populations.

Crop	Management	Worms/foot^2
Corn	Plow	1
Corn	No-till	2
Soybean	Plow	6
Soybean	No-till	14
Bluegrass/ clover	--	39
Dairy pasture	--	33

From Kladivko (8).

As a rule, earthworm numbers can be increased by reducing or eliminating tillage (especially fall tillage), not using a moldboard plow, reducing residue particle size (using a straw chopper on the combine), adding animal manure, and growing green manure crops. It is beneficial to leave as much surface residue as possible year-round.

Cropping systems that typically have the most earthworms are (in descending order) perennial cool-season grass grazed rotationally, warm-season perennial grass grazed rotationally, and annual croplands using no-till. Ridge-till and strip tillage will generally have more earthworms than clean tillage involving plowing and disking. Cool season grass rotationally grazed is highest because it provides an undisturbed (no-tillage) environment plus abundant organic matter from the grass roots and fallen grass litter. Generally speaking, worms want their food on top, and they want to be left alone.

Earthworms prefer a near-neutral soil pH, moist soil conditions, and plenty of plant residue on the soil surface. They are sensitive to certain pesticides and some incorporated fertilizers. Carbamate insecticides, including Furadan, Sevin, and Temik, are harmful to earthworms, notes worm biologist Clive Edwards of Ohio State University (4). Some insecticides in the organophosphate family are mildly toxic to earthworms, while synthetic pyrethroids are harmless to them (4). Most herbicides have little effect on worms except for the triazines, such as Atrazine, which are moderately toxic. Also, anhydrous ammonia kills earthworms in the injection zone because it dries the soil and temporarily increases the pH there. High rates of ammonium-based fertilizers are also harmful.

For more information on managing earthworms, order *The Farmer's Earthworm Handbook: Managing Your Underground Moneymakers*, by David Ernst. Ernst's book contains details on what earthworms need to live, how to increase worm numbers, the effects of tillage, manure, and livestock management on earthworms, how 193 chemicals affect earthworms, and more. See the **Additional Resources** section of this publication for ordering information. Also visit the earthworm Web sites listed in that section.

> As a rule, earthworm numbers can be increased by reducing or eliminating tillage.

Arthropods

In addition to earthworms, there are many other species of soil organisms that can be seen by the naked eye. Among them are sowbugs, millipedes, centipedes, slugs, snails, and springtails. These are the primary decomposers. Their role is to eat and shred the large particles of plant and animal residues. Some bury residue, bringing it into contact with other soil organisms that further decompose it. Some members of this group prey on smaller soil organisms. The springtails are small insects that eat mostly fungi. Their waste is rich in plant nutrients released after other fungi and bacteria decompose it. Also of interest are dung beetles, which play a valuable role in recycling manure and reducing livestock intestinal parasites and flies.

Bacteria

Bacteria are the most numerous type of soil organism: every gram of soil contains at least a million of these tiny one-celled organisms. There are many different species of bacteria, each with its own role in the soil environment. One of the major benefits bacteria provide for plants is in making nutrients available to them. Some species release nitrogen, sulfur, phosphorus, and trace elements from organic matter. Others break down soil minerals, releasing potassium, phosphorus, magnesium, calcium, and iron. Still other species make and release plant growth hormones, which stimulate root growth.

Several species of bacteria transform nitrogen from a gas in the air to forms available for plant use, and from these forms back to a gas again. A few species of bacteria fix nitrogen in the roots of legumes, while others fix nitrogen independently of plant association. Bacteria are responsible for converting nitrogen from ammonium to nitrate and back again, depending on certain soil conditions. Other benefits to plants provided by various species of bacteria include increasing the solubility of nutrients, improving soil structure, fighting root diseases, and detoxifying soil.

Fungi

Fungi come in many different species, sizes, and shapes in soil. Some species appear as threadlike colonies, while others are one-celled yeasts. Slime molds and mushrooms are also fungi. Many fungi aid plants by breaking down organic matter or by releasing nutrients from soil minerals. Fungi are generally quick to colonize larger pieces of organic matter and begin the decomposition process. Some fungi produce plant hormones, while others produce antibiotics including penicillin. There are even species of fungi that trap harmful plant-parasitic nematodes.

The mycorrhizae (my-cor-ry´-zee) are fungi that live either on or in plant roots and act to extend the reach of root hairs into the soil. Mycorrhizae increase the uptake of water and nutrients, especially phosphorus. They are particularly important in degraded or less fertile soils. Roots colonized by mycorrhizae are less likely to be penetrated by root-feeding nematodes, since the pest cannot pierce the thick fungal network. Mycorrhizae also produce hormones and antibiotics that enhance root growth and provide disease suppression. The fungi benefit by taking nutrients and carbohydrates from the plant roots they live in.

Actinomycetes

Actinomycetes (ac-tin-o-my´-cetes) are thread-like bacteria that look like fungi. While not as numerous as bacteria, they too perform vital roles in the soil. Like the bacteria, they help decompose organic matter into humus, releasing nutrients. They also produce antibiotics to fight diseases of roots. Many of these same antibiotics are used to treat human diseases. Actinomycetes are responsible for the sweet, earthy smell noticed whenever a biologically active soil is tilled.

Algae

Many different species of algae live in the upper half-inch of the soil. Unlike most other soil organisms, algae produce their own food through photosynthesis. They appear as a greenish film on the soil surface following a saturating rain. Algae improve soil structure by producing slimy substances that glue soil together into water-stable aggregates. Some species of algae (the blue-greens) can fix their own nitrogen, some of which is later released to plant roots.

Protozoa

Protozoa are free-living microorganisms that crawl or swim in the water between soil particles. Many soil protozoa are predatory, eating other microbes. One of the most common is an amoeba that eats bacteria. By eating and digesting bacteria, protozoa speed up the cycling of nitrogen from the bacteria, making it more available to plants.

Nematodes

Nematodes are abundant in most soils, and only a few species are harmful to plants. The harmless species eat decaying plant litter, bacteria, fungi, algae, protozoa, and other nematodes. Like other soil predators, nematodes speed the rate of nutrient cycling.

Soil organisms and soil quality

All these organisms—from the tiny bacteria up to the large earthworms and insects—interact with one another in a multitude of ways in the soil ecosystem. Organisms not directly involved in decomposing plant wastes may feed on each other or each other's waste products or the other substances they release. Among the substances released by the various microbes are vitamins, amino acids, sugars, antibiotics, gums, and waxes.

Roots can also release into the soil various substances that stimulate soil microbes. These substances serve as food for select organisms. Some scientists and practitioners theorize that plants use this means to stimulate the specific population of microorganisms capable of releasing or otherwise producing the kind of nutrition needed by the plants.

Research on life in the soil has determined that there are ideal ratios for certain key organisms in highly productive soils (9). The Soil Foodweb Lab, located in Oregon, tests soils and makes fertility recommendations that are based on this understanding. Their goal is to alter the makeup

Research on life in the soil has determined that there are ideal ratios for certain key organisms in highly productive soils.

of the soil microbial community so it resembles that of a highly fertile and productive soil. There are several different ways to accomplish this goal, depending on the situation. For more on the Soil Foodweb Lab, see the **Additional Resources** section of this publication.

Because we cannot see most of the creatures living in the soil and may not take time to observe the ones we can see, it is easy to forget about them. See Table 4 for estimates of typical amounts of various organisms found in fertile soil. There are many Web sites that provide in-depth information on soil organisms. Look for a list of these Web sites in the **Additional Resources** section. Many of these sites have color photographs of soil organisms and describe their benefits to soil fertility and plant growth.

Table 4. Weights of soil organisms in the top 7 inches of fertile soil.

Organism	Pounds of liveweight/acre
Bacteria	1000
Actinomycetes	1000
Molds	2000
Algae	100
Protozoa	200
Nematodes	50
Insects	100
Worms	1000
Plant roots	2000

From Bollen (10).

Organic Matter, Humus, and the Soil Foodweb

Like cattle and other farm animals, soil livestock require proper feed.

Understanding the role that soil organisms play is critical to sustainable soil management. Based on that understanding, focus can be directed toward strategies that build both the numbers and the diversity of soil organisms. Like cattle and other farm animals, soil livestock require proper feed. That feed comes in the form of organic matter.

Organic matter and *humus* are terms that describe somewhat different but related things. Organic matter refers to the fraction of the soil that is composed of both living organisms and once-living residues in various stages of decomposition. Humus is only a small portion of the organic matter. It is the end product of organic matter decomposition and is relatively stable. Further decomposition of humus occurs very slowly in both agricultural and natural settings. In natural systems, a balance is reached between the amount of humus formation and the amount of humus decay (11). This balance also occurs in most agricultural soils, but often at a much lower level of soil humus. Humus contributes to well-structured soil that, in turn, produces high-quality plants. It is clear that management of organic matter and humus is essential to sustaining the whole soil ecosystem.

The benefits of a topsoil rich in organic matter and humus are many. They include rapid decomposition of crop residues, granulation of soil into water-stable aggregates, decreased crusting and clodding, improved internal drainage, better water infiltration, and increased water and nutrient holding capacity. Improvements in the soil's physical structure facilitate easier tillage, increased water storage capacity, reduced erosion, better formation and harvesting of root crops, and deeper, more prolific plant root systems.

Soil organic matter can be compared to a bank account for plant nutrients. Soil containing 4% organic matter in the top seven inches has 80,000 pounds of organic matter per acre. That 80,000 pounds of organic matter will contain about 5.25% nitrogen, amounting to 4,200 pounds of nitrogen per acre. Assuming a 5% release rate during the growing season, the organic matter could supply 210 pounds of nitrogen to a crop. However, if the organic matter is allowed to degrade and lose nitrogen, purchased fertilizer will be necessary to prop up crop yields.

All the soil organisms mentioned previously, except algae, depend on organic matter as their food source. Therefore, to maintain their populations, organic matter must be renewed from plants growing on the soil, or from animal manure, compost, or other materials imported from off site. When soil livestock are fed, fertility is built up in the soil, and the soil will feed the plants.

Ultimately, building organic matter and humus levels in the soil is a matter of managing the soil's living organisms—something akin to wildlife management or animal husbandry. This entails working to maintain favorable conditions of moisture, temperature, nutrients, pH, and aeration. It also involves providing a steady food source of raw organic material.

Ultimately, building organic matter and humus in the soil is a matter of managing the soil's living organisms.

Soil Tilth and Organic Matter

A soil that drains well, does not crust, takes in water rapidly, and does not make clods is said to have good tilth. Tilth is the physical condition of the soil as it relates to tillage ease, seedbed quality, easy seedling emergence, and deep root penetration. Good tilth is dependent on aggregation—the process whereby individual soil particles are joined into clusters or "aggregates."

Aggregates form in soils when individual soil particles are oriented and brought together through the physical forces of wetting and drying or freezing and thawing. Weak electrical forces from calcium and magnesium hold soil particles together when the soil dries. When these aggregates become wet again, however, their stability is challenged, and they may break apart. Aggregates can also be held together by plant roots, earthworm activity, and by glue-like products produced by soil microorganisms. Earthworm-created aggregates are stable once they come out of the worm. An aggregate formed by physical forces can be bound together by fine root hairs or threads produced by fungi.

Aggregates can also become stabilized (remain intact when wet) through the by-products of organic matter decomposition by fungi and bacteria—chiefly gums, waxes, and other glue-like substances. These by-products cement the soil particles together, forming water-stable aggregates (Figure 2). The aggregate is then strong enough to hold together when wet—hence the term "water-stable."

USDA soil microbiologist Sara Wright named the glue that holds aggregates together "glomalin" after the Glomales group of common root-dwelling fungi (12). These fungi secrete a gooey protein known as glomalin through their hair-like filaments, or hyphae. When Wright measured glomalin in soil aggregates she found levels as high as 2% of their total weight in eastern U.S. soils. Soil aggregates from the West and Midwest had lower levels of glomalin. She found that tillage tends to lower glomalin levels. Glomalin levels and aggregation were

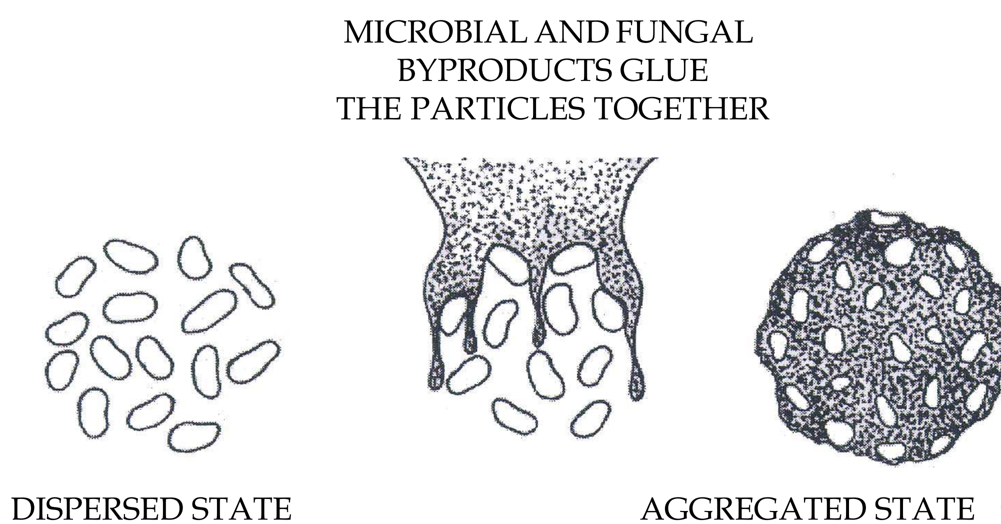


Figure 2. Microbial byproducts glue soil particles into water-stable aggregates.

higher in no-till corn plots than in tilled plots (12). Wright has a brochure describing glomalin and how it benefits soil, entitled *Glomalin, a Manageable Soil Glue*. To order this brochure see the **Additional Resources** section of this publication.

A well-aggregated soil allows for increased water entry, increased air flow, and increased water-holding capacity (13). Plant roots occupy a larger volume of well-aggregated soil, high in organic matter, as compared to a finely pulverized and dispersed soil, low in organic matter. Roots, earthworms, and soil arthropods can pass more easily through a well-aggregated soil (14). Aggregated soils also prevent crusting of the soil surface. Finally, well-aggregated soils are more erosion resistant, because aggregates are much heavier than their particle components. For a good example of the effect of organic matter additions on aggregation, as shown by subsequent increase in water entry into the soil, see Table 5.

Table 5. Water entry into the soil after 1 hour

Manure Rate (tons/acre)	Inches of water
0	1.2
8	1.9
16	2.7

Boyle et al. (13).

The opposite of aggregation is dispersion. In a dispersed soil, each individual soil particle is free to blow away with the wind or wash away with overland flow of water.

Clay soils with poor aggregation tend to be sticky when wet, and cloddy when dry. If the clay particles in these soils can be aggregated together, better aeration and water infiltration will result. Sandy soils can benefit from aggregation by having a small amount of dispersed clay that tends to stick between the sand particles and slow the downward movement of water.

Crusting is a common problem on soils that are poorly aggregated. Crusting results chiefly from the impact of falling raindrops. Rainfall causes clay particles on the soil surface to disperse and clog the pores immediately beneath the surface. Following drying, a sealed soil surface results in which most of the pore space has been drastically reduced due to clogging from dispersed clay particles. Subsequent rainfall is much more likely to run off than to flow into the soil (Figure 3).

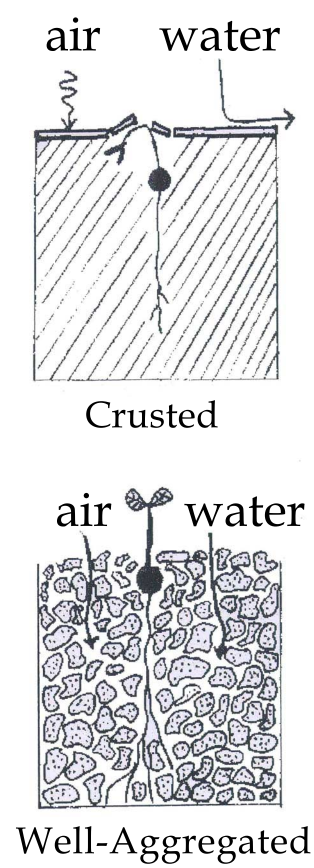


Figure 3. Effects of aggregation on water and air entry into the soil.
Derived from Land Stewardship Project Monitoring Toolbox (15).

Since raindrops start crusting, any management practices that protect the soil from their impact will decrease crusting and increase water flow into the soil. Mulches and cover crops serve this purpose well, as do no-till practices, which allow the accumulation of surface residue. Also, a well-aggregated soil will resist crusting because the water-stable aggregates are less likely to break apart when a raindrop hits them.

Long-term grass production produces the best-aggregated soils (16). A grass sod extends a mass of fine roots throughout the topsoil, contributing to the physical processes that help form aggregates. Roots continually remove water from soil microsites, providing local wetting and drying effects that promote aggregation. Fine root hairs also bind soil aggregates together.

Roots also produce food for soil microorganisms and earthworms, which in turn generate compounds that bind soil particles into water-stable aggregates. In addition, perennial grass sods provide protection from raindrops and erosion. Thus, a perennial cover creates a combination of conditions optimal for the creation and maintenance of well-aggregated soil.

The best-aggregated soils are those that have been in long-term grass production.

Conversely, cropping sequences that involve annual plants and extensive cultivation provide less vegetative cover and organic matter, and usually result in a rapid decline in soil aggregation. For more information on aggregation, see the soil quality information sheet entitled *Aggregate Stability* at the Soil Quality Institute's home page, <http://soils.usda.gov/sqi/files/sq_eig_1.pdf>. From there, click on Soil Quality Information Sheets, then click on Aggregate Stability.

Farming practices can be geared to conserve and promote soil aggregation. Because the binding substances are themselves susceptible to microbial degradation, organic matter needs to be replenished to maintain microbial populations and overall aggregated soil status. Practices should conserve aggregates once they are formed, by minimizing factors that degrade and destroy aggregation. Some factors that destroy or degrade soil aggregates are:

- bare soil surface exposed to the impact of raindrops
- removal of organic matter through crop production and harvest without return of organic matter to the soil
- excessive tillage
- working the soil when it is too wet or too dry
- use of anhydrous ammonia, which speeds up decomposition of organic matter
- excess nitrogen fertilization
- allowing the build-up of excess sodium from irrigation or sodium-containing fertilizers

Tillage, Organic Matter, and Plant Productivity

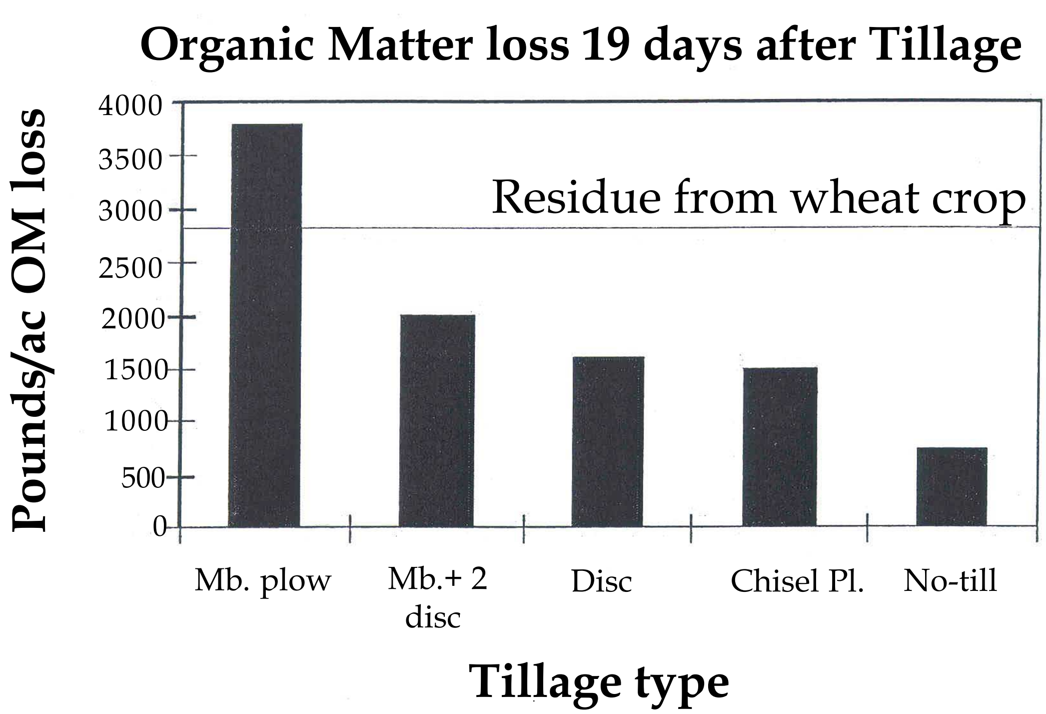
Several factors affect the level of organic matter that can be maintained in a soil. Among these are organic matter additions, moisture, temperature, tillage, nitrogen levels, cropping, and fertilization. The level of organic matter present in the soil is a direct function of how much organic material is being produced or added to the soil versus the rate of decomposition. Achieving this balance entails slowing the speed of organic matter decomposition, while increasing the supply of organic materials produced on site and/or added from off site.

Moisture and temperature also profoundly affect soil organic matter levels. High rainfall and temperature promote rapid plant growth, but these conditions are also favorable to rapid organic matter decomposition and loss. Low rainfall or low temperatures slow both plant growth and organic matter decomposition. The native Midwest prairie soils originally had a high amount of organic matter from the continuous growth and decomposition of perennial grasses, combined with a moderate temperature that did not allow for rapid decomposition of organic matter. Moist and hot tropical areas may appear lush because of rapid plant growth, but soils in these areas are low in nutrients. Rapid decomposition of organic matter returns nutrients back to the soil, where they are almost immediately taken up by rapidly growing plants.

Tillage can be beneficial or harmful to a biologically active soil, depending on what type of tillage is used and when it is done. Tillage affects both erosion rates and soil organic matter decomposition rates. Tillage can reduce the organic matter level in croplands below 1%, rendering them biologically dead. Clean tillage involving moldboard plowing and disking breaks down soil aggregates and leaves the soil prone to erosion from wind and water. The moldboard plow can bury crop residue and topsoil to a depth of 14 inches. At this depth, the oxygen level in the soil is so low that decomposition cannot proceed adequately. Surface-dwelling decomposer organisms suddenly find themselves suffocated and soon die. Crop residues that were originally on the surface but now have been turned under will putrefy in the oxygen-deprived zone. This rotting activity may give a putrid smell to the soil. Furthermore, the top few inches of the field are now often covered with subsoil having very little organic matter content and, therefore, limited ability to support productive crop growth.

The topsoil is where the biological activity happens—it's where the oxygen is. That's why a fence post rots off at the surface. In terms of organic matter, tillage is similar to opening the air vents on a wood-burning stove; adding organic matter is like adding wood to the stove. Ideally, organic matter decomposition should proceed as an efficient burn of the "wood" to release nutrients and carbohydrates to the soil organisms and create stable humus. Shallow tillage incorporates residue and speeds the decomposition of organic matter by adding oxygen that microbes need to become more active. In cold climates with a long dormant season, light tillage of a heavy residue may be beneficial; in warmer climates it is hard enough to maintain organic matter levels without any tillage.

As indicated in Figure 4, moldboard plowing causes the fastest decline of organic matter, no-till the least. The plow lays the soil up on its side, increasing the surface area exposed to oxygen. The other three types of tillage are intermediate in their ability to foster organic matter decomposition. Oxygen is the key factor here. The moldboard plow increases the soil surface area, allowing more air into the soil and speeding the decomposition rate. The horizontal line on Figure 4 represents the replenishment of organic matter provided by wheat stubble. With the moldboard plow, more than the entire organic matter contribution from the wheat straw is gone within only 19 days following tillage. Finally, the passage of heavy equipment increases compaction in the wheel tracks, and some tillage implements themselves compact the soil further, removing oxygen and increasing the chance that deeply buried residues will putrefy.



Reicosky & Lindstrom, 1995

Figure 4. Organic matter losses after various tillage practices (17).

Tillage also reduces the rate of water entry into the soil by removal of ground cover and destruction of aggregates, resulting in compaction and crusting. Table 6 shows three different tillage methods and how they affect water entry into the soil. Notice the direct relationship between tillage type, ground cover, and water infiltration. No-till has more than three times the water infiltration of the moldboard-plowed soil. Additionally, no-till fields will have higher aggregation from the organic matter decomposition on site. The surface mulch typical of no-till fields acts as a protective skin for the soil. This soil skin reduces the impact of raindrops and buffers the soil from temperature extremes as well as reducing water evaporation.

Table 6. Tillage effects on water infiltration and ground cover.

	Water Infiltration	Ground Cover
	mm/minute	Percent
No-till	2.7	48
Chisel Plow	1.3	27
Moldboard Plow	0.8	12

From Boyle et al., 1989 (13).

Both no-till and reduced-tillage systems provide benefits to the soil. The advantages of a no-till system include superior soil conservation, moisture conservation, reduced water runoff, long-term buildup of organic matter, and increased water infiltration. A soil managed without tillage relies on soil organisms to take over the job of plant residue incorporation formerly done by tillage. On the down side, no-till can foster a reliance on herbicides to control weeds and can lead to soil compaction from the traffic of heavy equipment.

Pioneering development work on chemical-free no-till farming is proceeding at several research stations and farms in the eastern U.S. Pennsylvania farmer Steve Groff has been farming no-till with minimal or no herbicides for several years. Groff grows cover crops extensively in his fields, rolling them down in the spring using a 10-foot rolling stalk chopper. This rolling chopper kills the rye or vetch cover crop and creates a nice no-till mulch into which he plants a variety of vegetable and grain crops. After several years of no-till production, his soils are mellow and easy to plant into. Groff farms 175 acres of vegetables, alfalfa, and grain crops on his Cedar Meadow Farm. Learn more about his operation in the **Farmer Profiles** section of this publication, by visiting his Web site, or by ordering his video (see **Additional Resources** section).

Other conservation tillage systems include ridge tillage, minimum tillage, zone tillage, and reduced tillage, each possessing some of the advantages of both conventional till and no-till. These systems represent intermediate tillage systems, allowing more flexibility than either a no-till or conventional till system might. They are more beneficial to soil organisms than a conventional clean-tillage system of moldboard plowing and disking.

Adding manure and compost is a recognized means for improving soil organic matter and humus levels. In their absence, perennial grass is the only crop that can regenerate and increase soil humus (18). Cool-season grasses build soil organic matter faster than warm-season grasses because they are growing much longer during a given year (18). When the soil is warm enough for soil organisms to decompose organic matter, cool-season grass is growing. While growing, it is producing organic matter and cycling minerals from the decomposing organic matter in the soil. In other words, there is a net gain of organic matter because the cool-season grass is producing organic matter faster than it is being used up. With warm-season grasses, organic matter production during the growing season can be slowed during the long dormant season from fall through early spring. During the beginning and end of this dormant period, the soil is still biologically active, yet no grass growth is proceeding (18). Some net accumulation of organic matter can occur under warm-season grasses, however. In a Texas study, switchgrass (a warm-season grass) grown for four years increased soil carbon content from 1.1% to 1.5% in the top 12 inches of soil (19). In hot and moist regions, a cropping rotation that includes several years of pasture will be most beneficial.

Effect of Nitrogen on Organic Matter

Excessive nitrogen applications stimulate increased microbial activity, which in turn speeds organic matter decomposition. The extra nitrogen narrows the ratio of carbon to nitrogen in the soil. Native or uncultivated soils have approximately 12 parts of carbon to each part of nitrogen, or a C:N ratio of 12:1. At this ratio, populations of decay bacteria are kept at a stable level (20), since additional growth in their population is limited by a lack of nitrogen. When large amounts of inorganic nitrogen are added, the C:N ratio is reduced, which allows the populations of decay organisms to explode as they decompose more organic matter with the now abundant nitrogen. While soil bacteria can efficiently use moderate applications of inorganic nitrogen accompanied by organic amendments (carbon), excess nitrogen results in decomposition of existing organic matter at a rapid rate. Eventually, soil carbon content may be reduced to a level where the bacterial populations are on a starvation diet. With little carbon available, bacterial populations shrink, and less of the free soil nitrogen is absorbed. Thereafter, applied nitrogen, rather than being cycled through microbial organisms and re-released to plants slowly over time, becomes subject to leaching. This can greatly reduce the efficiency of fertilization and lead to environmental problems.

Excessive nitrogen stimulates increased microbial activity, which in turn speeds organic matter decomposition.

To minimize the fast decomposition of soil organic matter, carbon should be added with nitrogen. Typical carbon sources—such as green manures, animal manure, and compost—serve this purpose well.

Amendments containing too high a carbon to nitrogen ratio (25:1 or more) can tip the balance the other way, resulting in nitrogen being tied up in an unavailable form. Soil organisms consume all the nitrogen in an effort to decompose the abundant carbon; tied up in the soil organisms, nitrogen remains unavailable for plant uptake. As soon as a soil microorganism dies and decomposes, its nitrogen is consumed by another soil organism, until the balance between carbon and nitrogen is achieved again.

Fertilizer Amendments and Biologically Active Soils

What are the soil mineral conditions that foster biologically active soils? Drawing from the work of Dr. William Albrecht (1888 to 1974), agronomist at the University of Missouri, we learn that balance is the key. Albrecht advocated bringing soil nutrients into a balance so that none were in excess or deficient. Albrecht's theory (also called base-saturation theory) is used to guide lime and fertilizer application by measuring and evaluating the ratios of positively charged nutrients (bases) held in the soil. Positively charged bases include calcium, magnesium, potassium, sodium, ammonium nitrogen, and several trace minerals. When optimum ratios of bases exist, the soil is believed to support high biological activity, have optimal physical properties (water intake and aggregation), and become resistant to leaching. Plants growing on such a soil are also balanced in mineral levels and are considered to be nutritious to humans and animals alike. Base saturation percentages that Albrecht's research showed to be optimal for the growth of most crops are:

Calcium	60—70%
Magnesium	10—20%
Potassium	2—5%
Sodium	0.5—3%
Other bases	5%

According to Albrecht, fertilizer and lime applications should be made at rates that will bring soil mineral percentages into this ideal range. This approach will shift the soil pH automatically into a desirable range without creating nutrient imbalances. The base saturation theory also takes into account the effect one nutrient may have on another and avoids undesirable interactions. For example, phosphorus is known to tie up zinc.

The Albrecht system of soil evaluation contrasts with the approach used by many state laboratories, often called the "sufficiency method." Sufficiency theory places little to no value on nutrient ratios, and lime recommendations are typically based on pH measurements alone. While in many circumstances base saturation and sufficiency methods will produce identical soil recommendations and similar results, significant differences can occur on a number of soils. For example, suppose we tested a cornfield and found a soil pH of 5.5 and base saturation for magnesium at 20% and calcium at 40%. Base saturation theory would call for liming with a high-calcium lime to raise the percent base saturation of calcium; the pH would rise accordingly. Sufficiency theory would not specify high-calcium lime and the grower might choose instead a high-magnesium dolomite lime that would raise the pH but worsen the balance of nutrients in the soil. Another way to look at these two theories is that the base saturation theory does not concern itself with pH to any great extent, but rather with the proportional amounts of bases. The pH will be correct when the levels of bases are correct.

Albrecht's ideas have found their way onto large numbers of American farms and into the programs of several agricultural consulting companies. Neal Kinsey, a soil fertility consultant in Charleston, Missouri, is a major proponent of the Albrecht approach. Kinsey was a student under Albrecht and is one of the leading authorities on the base-saturation method. He teaches a short course on the Albrecht system and provides a soil analysis service (21). His book, *Hands On Agronomy*, is widely recognized as a highly practical guide to the Albrecht system. ATTRA can provide more information on Albrecht Fertility Management Systems.

Several firms—many providing backup fertilizer and amendment products—offer a biological-farming program based on the Albrecht theory. Typically these firms offer broad-based soil analysis and recommend balanced fertilizer materials considered friendly to soil organisms. They avoid the use of some common fertilizers and amendments such as dolomite lime, potassium chloride, anhydrous ammonia, and oxide forms of trace elements because they are considered harmful to soil life. The publication *How to Get Started in Biological Farming* presents such a program. See the **Additional Resources** section for ordering information. For names of companies offering consulting and products, order the ATTRA publications *Alternative Soil Testing Laboratories* and *Sources of Organic Fertilizers and Amendments*. Both of these are also available on the ATTRA Web site located at <http://www.attra.ncat.org>.

Conventional Fertilizers

Commercial fertilizer can be a valuable resource to farmers in transition to a more sustainable system and can help meet nutrient needs during times of high crop nutrient demand or when weather conditions result in slow nutrient release from organic resources. Commercial fertilizers have the advantage of supplying plants with immediately available forms of nutrients. They are often less expensive and less bulky to apply than many natural fertilizers.

Not all conventional fertilizers are alike. Many appear harmless to soil livestock, but some are not. Anhydrous ammonia contains approximately 82% nitrogen and is applied subsurface as a gas. Anhydrous speeds the decomposition of organic matter in the soil, leaving the soil more compact as a result. The addition of anhydrous causes increased acidity in the soil, requiring 148 pounds of lime to neutralize 100 pounds of anhydrous ammonia, or 1.8 pounds of lime for every pound of nitrogen contained in the anhydrous (22). Anhydrous ammonia initially kills many soil microorganisms in the application zone. Bacteria and actinomycetes recover within one to two weeks to levels higher than those prior to treatment (23). Soil fungi, however, may take seven weeks to recover. During the recovery time, bacteria are stimulated to grow more, and decompose more organic matter, by the high soil nitrogen content. As a result, their numbers increase after anhydrous applications, then decline as available soil organic matter is depleted. Farmers commonly report that the long-term use of synthetic fertilizers, especially anhydrous ammonia, leads to soil compaction and poor tilth (23). When bacterial populations and soil organic matter decrease, aggregation declines, because existing glues that stick soil particles together are degraded, and no other glues are being produced.

Potassium chloride (KCl) (0-0-60 and 0-0-50), also known as muriate of potash, contains approximately 50 to 60% potassium and 47.5% chloride (24). Muriate of potash is made by refining potassium chloride ore, which is a mixture of potassium and sodium salts and clay from the brines of dying lakes and seas. The potential harmful effects from KCl can be surmised from the salt concentration of the material. Table 7 shows that, pound for pound, KCl is surpassed only by table salt on the salt index. Additionally, some plants such as tobacco, potatoes, peaches, and some legumes are especially sensitive to chloride. High rates of KCl must be avoided on such crops. Potassium sulfate, potassium nitrate, sul-po-mag, or organic sources of potassium may be considered as alternatives to KCl for fertilization.

Protecting soil from erosion is the first step toward a sustainable agriculture.

Sodium nitrate, also known as Chilean nitrate or nitrate of soda, is another high-salt fertilizer. Because of the relatively low nitrogen content of sodium nitrate, a high amount of sodium is added to the soil when normal applications of nitrogen are made with this material. The concern is that excessive sodium acts as a dispersant of soil particles, degrading aggregation. The salt index for KCl and sodium nitrate can be seen in Table 7.

Top$oil – Your Farm'$ Capital

Topsoil is the capital reserve of every farm. Ever since mankind started agriculture, erosion of topsoil has been the single largest threat to a

Table 7. Salt index for various fertilizers.

Material	Salt Index	Salt index per unit of plant food
Sodium chloride	153	2.9
Potassium chloride	116	1.9
Ammonium nitrate	105	3.0
Sodium nitrate	100	6.1
Urea	75	1.6
Potassium nitrate	74	1.6
Ammonium sulfate	69	3.3
Calcium nitrate	53	4.4
Anhydrous ammonia	47	.06
Sulfate-potash-magnesia	43	2.0
Di-ammonium phosphate	34	1.6
Monammonium phosphate	30	2.5
Gypsum	8	.03
Calcium carbonate	5	.01

soil's productivity—and, consequently, to farm profitability. This is still true today. In the U.S., the average acre of cropland is eroding at a rate of 7 tons per year (2). To sustain agriculture means to sustain soil resources, because that's the source of a farmer's livelihood.

The major productivity costs to the farm associated with soil erosion come from the replacement of lost nutrients and reduced water holding ability, accounting for 50 to 75% of productivity loss (2). Soil that is removed by erosion typically contains about three times more nutrients than the soil left behind and is 1.5 to 5 times richer in organic matter (2). This organic matter loss not only results in reduced water holding capacity and degraded soil aggregation, but also loss of plant nutrients, which must then be replaced with nutrient amendments.

Five tons of topsoil (the so-called tolerance level) can easily contain 100 pounds of nitrogen, 60 pounds of phosphate, 45 pounds of potash, 2 pounds of calcium, 10 pounds of magnesium, and 8 pounds of sulfur. Table 8 shows the effect of slight, moderate, and severe erosion on organic matter, soil phosphorus level, and plant-available water on a silt loam soil in Indiana (25).

Water erosion gets started when falling rainwater collides with bare ground and detaches soil particles from the parent soil body. After enough water builds up on the soil surface, following detachment, overland water flow transports suspended soil down-slope (Figure 5). Suspended soil in the runoff water abrades and detaches additional soil particles as the water travels overland. Preventing detachment is the most effective point of erosion control because it keeps the soil in place. Other erosion control practices seek to slow soil particle transport and cause soil to be deposited before it reaches streams. These methods are less effective at protecting the quality of soil within the field.

Commonly implemented practices to slow soil transport include terraces and diversions. Terraces, diversions, and many other erosion "control" practices are largely unnecessary if the ground stays covered year-round. For erosion prevention, a high percentage of ground cover is a good indicator of success, while bare ground is an "early warning" indicator for a high risk of erosion (27). Muddy runoff water and gullies are "too-late" indicators. The soil has already eroded by the time it shows up as muddy water, and it's too late to save soil already suspended in the water.

Table 8. Effect of erosion on organic matter phosphorus and plant-available water.

Erosion level	Organic matter	Phosphorus	Plant-available water
	%	Lbs./ac	%
Slight	3.0	62	7.4
Moderate	2.5	61	6.2
Severe	1.9	40	3.6

From Schertz et al., 1984. (24)

When erosion by water and wind occurs at a rate of 7.6 tons/acre/year it costs $40 per acre each year to replace the lost nutrients as fertilizer and around $17/acre/year to pump well irrigation water to replace the soil water holding capacity of that lost soil (26). The total cost of soil and water lost annually from U.S. cropland amounts to an on-site productivity loss of approximately $27 billion each year (2).

Protecting the soil from erosion is *the* first step toward a sustainable agriculture. Since water erosion is initiated by raindrop impact on bare soil, any management practice that protects the soil from raindrop impact will decrease erosion and increase water entry into the soil. Mulches, cover crops, and crop residues serve this purpose well.

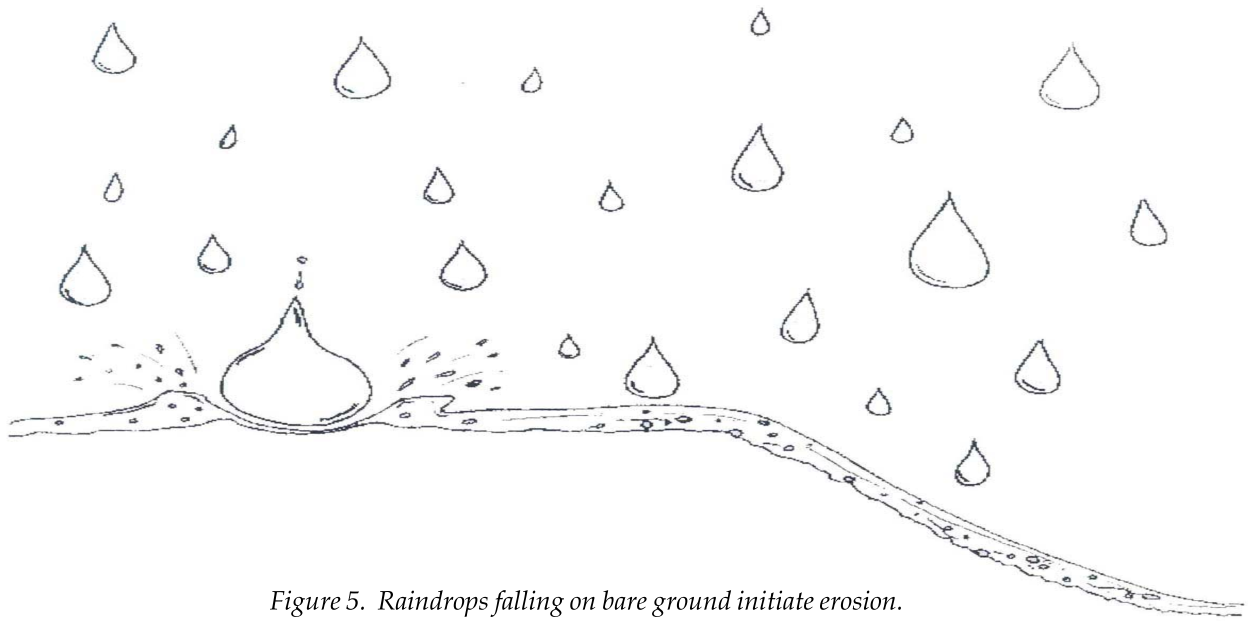


Figure 5. Raindrops falling on bare ground initiate erosion. Drawing from cropland monitoring guide (27).

Additionally, well-aggregated soils resist crusting because water-stable aggregates are less likely to break apart when the raindrop hits them. Adequate organic matter with high soil biological activity leads to high soil aggregation.

Many studies have shown that cropping systems that maintain a soil-protecting plant canopy or residue cover have the least soil erosion. This is universally true. Long-term cropping studies begun in 1888 at the University of Missouri provide dramatic evidence of this. Gantzer and colleagues (28) examined the effects of a century of cropping on soil erosion. They compared depth of topsoil remaining after 100 years of cropping (Table 9). As the table shows, the cropping system that maintained the highest amount of permanent ground cover (timothy grass) had the greatest amount of topsoil left.

Table 9. Topsoil depth remaining after 100 years of different cropping practices.

Crop Sequence	Inches of topsoil remaining
Continuous Corn	7.7
6-year rotation*	12.2
Continuous timothy grass	17.4

**Corn, oats, wheat, clover, timothy*
From: Gantzer et al. (28).

The researchers commented that subsoil had been mixed with topsoil in the continuous corn plots from plowing, making the real topsoil depth less than was apparent. In reality, all the topsoil was lost from the continuous corn plots in only 100 years. The rotation lost about half the topsoil over 100 years. How can we feed future generations with this type of farming practice?

In a study of many different soil types in each of the major climatic zones of the U.S., researchers showed dramatic differences in soil erosion when comparing row crops to perennial sods. Row crops consisted of cotton or corn, and sod crops were bluegrass or bermuda grass. On average, the row crops eroded more than 50 times more soil than did the perennial sod crops. The two primary influencing factors are ground cover and tillage. The results are shown in Table 10.

So, how long do fields have before the topsoil is gone? This depends on where in the country the field is located. Some soils naturally have very thick topsoil, while other soils have thin topsoil over rock or gravel. Roughly 8 tons/acre/year of soil-erosion loss amounts to the thickness of a dime spread over an acre. Twenty dimes stack up to 1-inch high. So a landscape with an 8-ton erosion rate would lose an inch of topsoil about every 20 years. On a soil with a thick topsoil, this amount is barely detectable within a person's lifetime and may not be no-

Table 10. Effect of cropping on soil erosion rates

Soil type	Location	Slope	Row crop soil loss	Sod soil loss
	State	*%*	*Tons/ac*	*Tons/ac*
Silt loam	Iowa	9	38	.02
Loam	Missouri	8	51	.16
Silt loam	Ohio	12	99	.02
Fine sandy loam	Oklahoma	7.7	19	.02
Clay loam	N. Carolina	10	31	.31
Fine sandy loam	Texas	8.7	24	.08
Clay	Texas	4	21	.02
Silt loam	Wisconsin	16	111	.10
Average	Average	9.4	49	.09

Adapted from Shiflet and Darby, 1985 (29).

ticed. Soils with naturally thin topsoils or topsoils that have been previously eroded can be transformed from productive to degraded land within a generation.

Forward-thinking researcher Wes Jackson, of the Land Institute, waxes eloquent about how tillage has become engrained in human culture since we first began farming. Beating our swords into plowshares surely embodies the triumph of good over evil. Someone who creates something new is said to have "plowed new ground." "Yet the plowshare may well have destroyed more options for future generations than the sword" (30).

Tillage for the production of annual crops is the major problem in agriculture, causing soil erosion and the loss of soil quality. Any agricultural practice that creates and maintains bare ground is inherently less sustainable than practices that keep the ground covered throughout the year. Wes Jackson has spent much of his career developing perennial grain crops and cropping systems that mimic the natural prairie. Perennial grain crops do not require tillage to establish year after year, and the ground is left covered. Ultimately, this is the future of grain production and truly represents a new vision for how we produce food. The greatest research need in agriculture today is breeding work to develop perennial crops that will replace annual crops requiring tillage. Farming practices using annual crops in ways that mimic perennial systems, such as no-till and cover crops, are our best alternative until perennial systems are developed.

Summary of Part I

Soil management involves stewardship of the soil livestock herd. The primary factors affecting organic matter content, build-up, and decomposition rate in soils are oxygen content, nitrogen content, moisture content, temperature, and the addition and removal of organic materials. All these factors work together all the time. Any one can limit the others. These are the factors that affect the health and reproductive rate of organic matter decomposer organisms. Managers need to be aware of these factors when making decisions about their soils. Let's take them one at a time.

Increasing oxygen speeds decomposition of organic matter. Tillage is the primary way extra oxygen enters the soil. Texture also plays a role, with sandy soils having more aeration than heavy clay soils. *Nitrogen content* is influenced by fertilizer additions. Excess nitrogen, without the addition of carbon, speeds the decomposition of organic matter. *Moisture content* affects decomposition rates. Soil microbial populations are most active over cycles of wetting and drying. Their populations increase following wetting, as the soil dries out. After the soil becomes dry, their activity diminishes. Just like humans, soil organisms are profoundly affected by *temperature*. Their activity is highest within a band of optimum temperature, above and below which their activity is diminished.

Adding organic matter provides more food for microbes. To achieve an increase of soil organic matter, additions must be higher than removals. Over a given year, under average conditions, 60 to 70 percent of the carbon contained in organic residues added to soil is lost as carbon dioxide (20). Five to ten percent is assimilated into the organisms that decomposed the organic residues, and the rest becomes 'new' humus. It takes decades for new humus to develop into stable humus, which imparts the nutrient-holding characteristics humus is known for (20). The end result of adding a ton of residue would be 400 to 700 pounds of new humus. One percent organic matter weighs 20,000 pounds per acre. A 7-inch depth of topsoil over an acre weighs 2 million pounds. Building organic matter is a *slow* process.

It is more feasible to stabilize and maintain the humus present, before it is lost, than to try to rebuild it. The value of humus is not fully realized until it is severely depleted (20). If your soils are high in humus now, work hard to preserve what you have. The formation of new humus is essential to maintaining old humus, and the decomposition of raw organic matter has many benefits of its own. Increased aeration caused by tillage coupled with the absence of organic carbon in fertilizer materials has caused more than a 50% decline in native humus levels on many U.S. farms (20).

Appropriate mineral nutrition needs to be present for soil organisms and plants to prosper. Adequate levels of calcium, magnesium, potassium, phosphorus, sodium, and the trace elements should be present, but not in excess. The base saturation theory of soil management helps guide decision-making toward achieving optimum levels of these nutrients in the soil. Several books have been written on balancing soil mineral levels, and several consulting firms provide soil analysis and fertility recommendation services based on this theory.

Commercial fertilizers have their place in sustainable agriculture. Some appear harmless to soil livestock and provide nutrients at times of high nutrient demand from crops. Anhydrous ammonia and potassium chloride cause problems, however. As noted above, anhydrous kills soil organisms in the injection zone. Bacteria and actinomycetes recover within a few weeks, but fungi take longer. The increase in bacteria, fed by highly available nitrogen from the anhydrous, speeds the decomposition of organic matter. Potassium chloride has a high salt index, and some plants and soil organisms are sensitive to chloride.

Topsoil is the farmer's capital. Sustaining agriculture means sustaining the soil. Maintaining ground cover in the form of cover crops, mulch, or crop residue for as much of the annual season as possible achieves the goal of sustaining the soil resource. Any time the soil is tilled and left bare it is susceptible to erosion. Even small amounts of soil erosion are harmful over time. It is not easy to see the effects of erosion over a human lifetime; therefore, erosion may go unnoticed. Tillage for production of annual crops has created most of the erosion associated with agriculture. Perennial grain crops not requiring tillage provide a promising alternative for drastically improving the sustainability of future grain production.

Summary of Sustainable Soil Management Principles

- Soil livestock cycle nutrients and provide many other benefits.
- Organic matter is the food for the soil livestock herd.
- The soil should be covered to protect it from erosion and temperature extremes.
- Tillage speeds the decomposition of organic matter.
- Excess nitrogen speeds the decomposition of organic matter; insufficient nitrogen slows down organic matter decomposition and starves plants.

- Moldboard plowing speeds the decomposition of organic matter, destroys earthworm habitat, and increases erosion.

- To build soil organic matter, the production or addition of organic matter must exceed the decomposition of organic matter.

- Soil fertility levels need to be within acceptable ranges before a soil-building program is begun.

Part II. Management Steps to Improve Soil Quality

1. Assess Soil Health and Biological Activity on Your Farm

A basic soil audit is the first and sometimes the only monitoring tool used to assess changes in the soil. Unfortunately, the standard soil test done to determine nutrient levels (P, K, Ca, Mg, etc.) provides no information on soil biology and physical properties. Yet most of the farmer-recognized criteria for healthy soils (see p. 2) include, or are created by, soil organisms and soil physical properties. A better appreciation of these biological and physical soil properties, and how they affect soil management and productivity, has resulted in the adoption of several new soil health assessment techniques, which are discussed below.

The USDA Soil Quality Test Kit

The USDA Soil Quality Institute provides a Soil Quality Test Kit Guide developed by Dr. John Doran and associates at the Agricultural Research Service's office in Lincoln, Nebraska. Designed for field use, the kit allows the measurement of water infiltration, water holding capacity, bulk density, pH, soil nitrate, salt concentration, aggregate stability, earthworm numbers, and soil respiration. Components necessary to build a kit include many items commonly available—such as pop bottles, flat-bladed knives, a garden trowel, and plastic wrap. Also necessary to do the tests is some equipment that is not as readily available, such as hypodermic needles, latex tubing, a soil thermometer, an electrical conductivity meter, filter paper, and an EC calibration standard. The Soil Quality Test Kit Guide can be ordered from the USDA through the Soil Quality Institute's Web page, <http://soils.usda.gov/sqi/files/KitGuideComplete.pdf>. The 88-page on-line version of the guide is available in Adobe Acrobat Reader format through the above Web page and may be printed out. A summary of the tests is also available from the Web page. To order a print version, see the Soil Quality Institute reference under **Additional Resources**.

A greatly simplified and quick soil quality assessment is available at the Soil Quality Institute's Web page as well, by clicking on "Getting to Know your Soil," near the bottom of the homepage. This simplified method involves digging a hole and making some observations. Here are a few of the procedures shown at this Web site: Dig a hole 4 to 6 inches below the last tillage depth and observe how hard the digging is. Inspect plant roots to see whether there is a lot of branching and fine root hairs or whether the roots are balled-up. A lack of fine root hairs indicates oxygen deprivation, while sideways growth indicates a hardpan. The process goes on to assess earthworms, soil smell, and aggregation. Another useful, hands-on procedure for assessing pasture soils is discussed in the ATTRA publication *Assessing the Pasture Soil Resource*.

Early Warning Monitoring for Croplands

A cropland monitoring guide has been published by the Center for Holistic Management (27). The guide contains a set of soil health indicators that are measurable in the field. No fancy equipment is needed to make the assessments described in this monitoring guide. In fact, all the equipment is cheap and locally available for almost any farm. Simple measurements can help determine the health of croplands in terms of the effectiveness of the nutrient cycle and water cycle, and the diversity of some soil organisms. Assessments of living organisms, aggregation, water infiltration, ground cover, and earthworms can be made using this guide. The monitoring guide is easy to read and understand and comes with a field sheet to record observations. It is available for $12 from the Savory Center for Holistic Management (see **Additional Resources**).

Direct Assessment of Soil Health

Some quick ways to identify a healthy soil include feeling it and smelling it. Grab a handful and take a whiff. Does it have an earthy smell? Is it a loose, crumbly soil with some earthworms present? Dr. Ray Weil, soil scientist at the University of Maryland, describes how he would make a quick evaluation of a soil's health in just five minutes (31).

> Look at the surface and see if it is crusted, which tells something about tillage practices used, organic matter, and structure. Push a soil probe down to 12 inches, lift out some soil and feel its texture. If a plow pan were present it would have been felt with the probe. Turn over a shovelful of soil to look for earthworms and smell for actinomycetes, which are microorganisms that help compost and stabilize decaying organic matter. Their activity leaves a fresh earthy smell in the soil.

Two other easy observations are to count the number of soil organisms in a square foot of surface crop residue and to pour a pint of water on the soil and record the time it takes to sink in. Comparisons can be made using these simple observations, along with Ray Weil's evaluation above, to determine how farm practices affect soil quality. Some of the soil quality assessment systems discussed above use these and other observations and provide record keeping sheets to record your observations.

A Simple Erosion Demonstration

This simple procedure demonstrates the value of ground cover. Tape a white piece of paper near the end of a three-foot-long stick. Hold the stick in one hand so as to have the paper end within one inch of a bare soil surface (see Figure 6). Now pour a pint of water onto the bare soil within two to three inches of the white paper and observe the soil accumulation on the white paper. Tape another piece of white paper to the stick and repeat the operation, this time over soil with 100% ground cover, and observe the accumulation of soil on the paper. Compare the two pieces of paper. This simple test shows how effective ground cover can be at preventing soil particles from detaching from the soil surface.

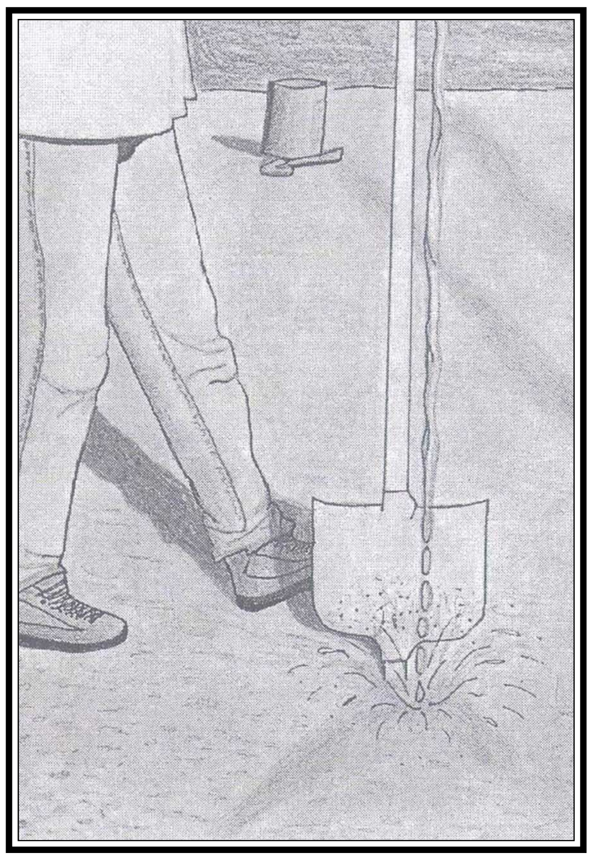


Figure 6. Simple erosion test.
Drawing from Cropland monitoring guide (27).

2. Use Tools and Techniques to Build Soil

Can a cover crop be worked into your rotation? How about a high-residue crop or perennial sod? Are there economical sources of organic materials or manure in your area? Are there ways to reduce tillage and nitrogen fertilizer? Where feasible, bulky organic amendments may be added to supply both organic matter and plant nutrients. It is particularly useful to account for nutrients when organic fertilizers and amendments are used. Start with a soil test and a nutrient analysis of the material you are applying. Knowing the levels of nutrients needed by the crop guides the amount of amendments applied and can lead to significant reductions in fertilizer cost. The nutrient composition of organic materials can vary, which is all the more reason to determine the amount you have with appropriate testing. In addition to containing the major plant nutrients, organic fertilizers can supply many essential micronutrients. Proper calibration of the spreading equipment is important to ensure accurate application rates.

Animal Manure

Manure is an excellent soil amendment, providing both organic matter and nutrients. The amount of organic matter and nitrogen in animal manure depends on the feed the animals consumed, type of bedding used (if any), and whether the manure is applied as a solid or liquid. Typical rates for dairy manure would be 10 to 30 tons per acre or 4,000 to 11,000 gallons of liquid for corn. At these rates the crop would get between 50 and 150 pounds of available nitrogen per acre. Additionally, lots of carbon would be added to the soil, resulting in no loss of soil organic matter. Residues from crops grown with this manure application and left on the soil would also contribute organic matter.

A common problem with using manure as a nutrient source is that application rates are usually based on the nitrogen needs of the crop.

However, a common problem with using manure as a nutrient source is that application rates are usually based on the nitrogen needs of the crop. Because some manures have about as much phosphorus as they do nitrogen, this often leads to a buildup of soil phosphorus. A classic example is chicken litter applied to crops that require high nitrogen levels, such as pasture grasses and corn. Broiler litter, for example, contains approximately 50 pounds of nitrogen and phosphorus and about 40 pounds of potassium per ton. Since an established fescue pasture needs twice as much nitrogen as it does phosphorus, a common fertilizer application would be about 50 pounds of nitrogen and 30 pounds of phosphorus per acre. If a ton of poultry litter were applied to supply the nitrogen needs of the fescue, an over-application of phosphorus would result, because the litter has about the same levels of nitrogen and phosphorus. Several years of litter application to meet nitrogen needs can build up soil phosphorus to excessive levels. One easy answer to this dilemma is to adjust the manure rate to meet the phosphorus needs of the crop and to supply the additional nitrogen with fertilizer or a legume cover crop. On some farms this may mean that more manure is being produced than can be safely used on the farm. In this case, farmers may need to find a way to process and sell (or barter) this excess manure to get it off the farm.

Compost

Composting farm manure and other organic materials is an excellent way to stabilize their nutrient content. Composted manure is also easier to handle, less bulky, and better smelling than raw manure. A significant portion of raw-manure nutrients are in unstable, soluble forms. Such unstable forms are more likely to run off if surface-applied, or to leach if tilled into the soil. Compost is not as good a source of readily available plant nutrients as raw manure. But compost releases its nutrients slowly, thereby minimizing losses. Quality compost contains more humus than its raw components because primary decomposition has occurred during the composting process. However, it does not contribute as much of the sticky gums and waxes that aggregate soil particles together as does raw manure, because these substances are also released during the primary decomposition phase. Unlike manure, compost can be used at almost any rate without burning plants. In fact, some greenhouse potting mixes contain 20 to 30% compost. Compost (like manure) should be analyzed by a laboratory to determine the nutrient value of a particular batch and to ensure that it is being used effectively to produce healthy crops and soil, and not excessively so that it contributes to water pollution.

Composting also reduces the bulk of raw organic materials—especially manures, which often have a high moisture content. However, while less bulky and easier to handle, composts can be expensive to buy. On-farm composting cuts costs dramatically, compared with buying compost. For more comprehensive information on composting at the farm or the municipal level, see the ATTRA publication *Farm-Scale Composting Resource List*.

Cover Crops and Green Manures

Many types of plants can be grown as cover crops. Some of the more common ones include rye, buckwheat, hairy vetch, crimson clover, subterranean clover, red clover, sweet clover, cowpeas, millet, and forage sorghums. Each of these plants has some advantages over the others and differs in its area of adaptability. Cover crops can maintain or increase soil organic matter if they are allowed to grow long enough to produce high herbage. All too often, people get in a hurry and take out a good cover crop just a week or two before it has reached its full potential. Hairy vetch or crimson clover can yield up to 2.5 tons per acre if allowed to go to 25% bloom stage. A mixture of rye and hairy vetch can produce even more.

In addition to organic matter benefits, legume cover crops provide considerable nitrogen for crops that follow them. Consequently, the nitrogen rate can be reduced following a productive legume cover crop taken out at the correct time. For example, corn grown following two tons of hairy vetch should produce high yields of grain with only half of the normal nitrogen application.

When small grains such as rye are used as cover crops and allowed to reach the flowering stage, additional nitrogen may be required to help offset the nitrogen tie-up caused by the high carbon addition of the rye residue. The same would be true of any high-carbon amendment, such as sawdust or wheat straw. Cover crops also suppress weeds, help break pest cycles, and through their pollen and nectar provide food sources for beneficial insects and honeybees. They can also cycle other soil nutrients, making them available to subsequent crops as the green manure decomposes. For more information on cover crops, see ATTRA's *Overview of Cover Crops and Green Manures*. This publication is comprehensive and provides many references to other available information on growing cover crops.

Humates

Humates and humic acid derivatives are a diverse family of products, generally obtained from various forms of oxidized coal. Coal-derived humus is essentially the same as humus extracts from soil, but there has been a reluctance in some circles to accept it as a worthwhile soil additive. In part, this stems from a belief that only humus derived from recently decayed organic matter is beneficial. It is also true that the production and recycling of organic matter in the soil cannot be replaced by coal-derived humus.

However, while sugars, gums, waxes and similar materials derived from fresh organic-matter decay play a vital role in both soil microbiology and structure, they are not humus. Only a small portion of the organic matter added to the soil will ever be converted to humus. Most will return to the atmosphere as carbon dioxide as it decays.

Some studies have shown positive effects of humates, while other studies have shown no such effects. Generally, the consensus is that they work well in soils with low organic matter. In small amounts they do not produce positive results on soils already high in organic matter; at high rates they may tie up soil nutrients.

There are many humate products on the market. They are not all the same. Humate products should be evaluated in a small test plot for cost effectiveness before using them on a large scale. Salespeople sometimes make exaggerated claims for their products. ATTRA can provide more information on humates upon request.

Reduced Tillage

While tillage has become common to many production systems, its effects on the soil can be counter-productive. Tillage smoothes the soil surface and destroys natural soil aggregations and earthworm channels. Porosity and water infiltration decrease following most tillage operations. Plow pans may develop in many situations, particularly if soils are plowed with heavy equipment or when the soil is wet. Tilled soils have much higher erosion rates than soils left covered with crop residue.

Because of all the problems associated with conventional tillage operations, acreage under reduced tillage systems is increasing in America. Any tillage system that leaves in excess of 30% surface residue is considered a "conservation tillage" system by USDA (32). Conservation tillage includes no-till, zero-till, ridge-till, zone-till, and some variations of chisel plowing and disking. These conservation till strategies and techniques allow for establishing crops into the previous crop's residues, which are purposely left on the soil surface. The principal benefits of conservation tillage are reduced soil erosion and improved water retention in the soil, resulting in more drought resistance. Additional benefits that many conservation tillage systems provide include reduced fuel consumption, flexibility in planting and harvesting, reduced labor requirements, and improved soil tilth. Two of the most common conservation tillage systems are ridge tillage and no-till.

Ridge tillage is a form of conservation tillage that uses specialized planters and cultivators to maintain permanent ridges on which row crops are grown. After harvest, crop residue is left until planting time. To plant the next crop, the planter places the seed in the top of the ridge after pushing residue out of the way and slicing off the surface of the ridge top. Ridges are re-formed during the last cultivation of the crop.

Often, a band of herbicide is applied to the ridge top during planting. With banded herbicide applications, two cultivations are generally used: one to loosen the soil and another to create the ridge later in the season. No cultivation may be necessary if the herbicide is applied by broadcasting rather than banding. Because ridge tillage relies on cultivation to control weeds and reform ridges, this system allows farmers to further reduce their dependence on herbicides, compared with either conventional till or strict no-till systems.

Maintenance of the ridges is key to successful ridge tillage systems. The equipment must accurately reshape the ridge, clean away crop residue, plant in the ridge center, and leave a viable seedbed. Not only does the ridge-tillage cultivator remove weeds, it also builds up the ridge. Harvesting in ridged fields may require tall, narrow dual wheels fitted to the combine. This modification permits the combine to straddle several rows, leaving the ridges undisturbed. Similarly, grain trucks and wagons cannot be driven randomly through the field. Maintenance of the ridge becomes a consideration for each process.

Conventional no-till methods have been criticized for a heavy reliance on chemical herbicides for weed control. Additionally, no-till farming requires careful management and expensive machinery for some applications. In many cases, the spring temperature of untilled soil is lower than that of tilled soil. This lower temperature can slow germination of early-planted corn or delay planting dates. Also, increased insect and rodent pest problems have been reported. On the positive side, no-till methods offer excellent soil erosion prevention and decreased trips across the field. On well-drained soils that warm adequately in the spring, no-till has provided the same or better yields than conventional till.

A recent equipment introduction into the no-till arena is the so-called "no-till cultivator." These cultivators permit cultivation in heavy residue and provide a non-chemical option to post-emergent herbicide applications. Farmers have the option to band herbicide in the row and use the no-till cultivator to clean the middles as a way to reduce herbicide use. ATTRA can provide a number of resource contacts on cultural methods, equipment, and management for conservation-till cropping systems.

Minimize Synthetic Nitrogen Use

If at all possible, add carbon with nitrogen sources. Animal manure is a good way to add both carbon and nitrogen. Growing legumes as a green manure or rotation crop is another way. When using nitrogen fertilizer, try to do it at a time when a heavy crop residue is going onto the soil, too. For example, a rotation of corn, beans, and wheat would do well with nitrogen added after the corn residue was rolled down or lightly tilled in. Spring-planted soybeans would require no nitrogen. A small amount of nitrogen could be applied in the fall for the wheat. Following the wheat crop, a legume winter-annual cover crop could be planted. In the spring, when the cover crop is taken out, nitrogen rates for the corn would be reduced to account for the nitrogen in the legume. Avoid continual hay crops accompanied by high nitrogen fertilization. The continual removal of hay accompanied by high nitrogen speeds the decomposition of soil organic matter. Heavy fertilization of silage crops, where all the crop residue is removed (especially when accompanied by tillage), speeds soil decline and organic matter depletion.

3. Continue to Monitor for Indicators of Success or Failure

As you experiment with new practices and amendments, continue to monitor the soil for changes using some of the tools discussed above in **Assess Soil Health and Biological Activity**. Several of these monitoring guides have sheets you can use in the field to record data and use for future comparison after changes are made to the farming practices. Review the principles of sustainable soil management and find ways to apply them in your operation. If the thought of pulling everything together seems overwhelming, start with only one or two new practices and build on them. Seek additional motivation by reading the next section on people who have successfully built their soils.

Photo by USDA NRCS

Part III. Examples of Successful Soil Builders (Farmer Profiles)

Steve Groff

Steve and his family produce vegetables, alfalfa, and grain crops on 175 acres in Lancaster County, Pennsylvania. When Steve took over operation of the family farm 15 years ago, his number one concern was eliminating soil erosion. Consequently, he began using cover crops extensively in his fields. In order to transform his green cover crop into no-till mulch, Steve uses a 10-foot Buffalo rolling stalk chopper. Under the hitch-mounted frame, the stalk chopper has two sets of rollers running in tandem. These rollers can be adjusted for light or aggressive action and set for continuous coverage. Steve says the machine can be run up to eight miles an hour and does a good job of killing the cover crop and pushing it right down on the soil. It can also be used to flatten down other crop residues after harvest. Steve improved his chopper by adding independent linkages and springs to each roller. This modification makes each unit more flexible and allows continuous use over uneven terrain. Other farmers report similar results using a disk harrow with the gangs set to run straight or at a slight angle. Following his cover crop chopping, Steve transplants vegetable seedlings into the killed mulch; sweet corn and snap beans are direct-seeded. Since conversion to a cover crop mulch system, his soils are protected from erosion and have become much mellower. For more information on his system, order Steve's videos listed under **Additional Resources**, or visit his Web page at <http://www.cedarmeadowfarm.com/about.html>. At Steve's Web site you can see photos of his cover crop roller and no-till transplanter in action, as well as test-plot results comparing flail mowing, rolling, and herbicide killing of cover crops.

Bob Willett

Bob started no-tilling 20 years ago on his corn and soybean farm in Pride, Kentucky. He not only reduced his machinery costs by switching to no-till but also made gains in conserving topsoil. His goal is to develop a healthy level of humus in the top two inches, which keeps the seed zone loose. He has stopped the sidewall compaction in the seed slot that still plagues his neighbors during wet springs. He attributes this improvement to the increase in humus and organic matter. His soil surface layer is crumbly and doesn't smear when the disk openers pass through. Bob proclaims that earthworms take the place of tillage by incorporating residue and converting it to humus. Worms help aerate his soil and improve internal drainage, which contributes to good rooting for his crops (33).

David Iles

On the Iles's North Carolina dairy farm the soil has actually changed from red to a dark, almost black color since conversion to no-till in 1970. David first learned about no-till from his college professor at North Carolina State University in 1964. Before he switched to no-till, David's corn silage yielded between 12 and 15 tons per acre in years with adequate rainfall and 4 to 5 tons in dry years—indicating that moisture was his major limiting factor (34). David realized that his water runoff losses and soil erosion were a direct result of tillage. Addressing the root cause of the problem, he switched to no-till and began to spread manure on 1/3 of his land annually. Since these changes, soil water is no longer limiting. With adequate rainfall he makes nearly 20 tons of silage now. David says his land is vastly more productive, with increased cation exchange capacity and increased phosphorus levels due to the humus present in his soil. Though his soil pH ranges in the 5.6 to 5.8 level, he applies no lime. His fields are more productive now than when he applied lime in the '70s and more productive than those of his neighbors who currently use lime and fertilizer.

David laments that this country has lost half of its topsoil in less than 100 years (34). North Carolina State agronomist Bobby Brock agrees and says that for the first time in history we have the opportunity to produce food and build soil at the same time. David reasons that no-till is the way to improve the soil structure, increase tilth, and increase productivity while still practicing intensive agriculture. He realizes that organic matter is the engine that drives his system and provides food for earthworms and microorganisms. David built his soil by fallowing out 20 to 25 acres of his 380-acre farm each year. On these fallow acres he spreads manure and then sows crops that are not harvested but grown just for their organic matter. Even weeds are not clipped but left for their organic matter. David loves his earthworms and says they are the best employees he has. "They work all the time and eat dirt for a living" (34).

His best field is one he cleared himself in the '70s. In spite of traditional native pHs in the high 4s in his area, he did not lime this new ground but instead just planted rye on it. He had a fine rye crop that year, so he applied manure liberally and planted rye a second time. His second rye crop was excellent as well and was followed by corn the third year. That field yielded the most corn on the entire farm. This field has been in continuous corn since 1981 and has never been fertilized with conventional products or tilled (34). This field has a pH of

6.1 at a 6-inch depth, an exchange capacity of 8, and an 80% base saturation. David believes this field's productivity is high because it has never been harmed by tillage.

References

1) Cramer, Craig. 1994. Test your soils' health—first in a series. The New Farm. January. p. 17–21.

2) Pimentel, D., et al. 1995. Environmental and economic costs of soil erosion and conservation benefits. Science. Vol. 267, No. 24. p. 1117–1122.

3) U.S. Department of Agriculture. 1998. Soil Biodiversity. Soil Quality Information Sheet, Soil Quality Resource Concerns. January. 2 p.

4) Edwards, Clive A., and P.J. Bohlen. 1996. Biology and Ecology of Earthworms. Chapman and Hall, New York. 426 p.

5) Edwards, Clive A., and Ian Burrows. 1988. The potential of earthworm composts as plant growth media. p. 211-219. *In*: Earthworms in Waste and Environmental Management. C.A. Edwards and E.F. Neuhauser (eds.). SPB Academic Publishing, The Hague, The Netherlands.

6) Graff, O. 1971. Stikstoff, phosphor undkalium in der regenwormlosung auf derwiesenversuchsflche des sollingprojektes. Annales de Zoologie: Ecologie Animale. Special Publication 4. p. 503–512.

7) Anon. 1997. Product choices help add to worm counts. Farm Industry News. February. p. 64

8) Kladivko, Eileen J. No date. Earthworms and crop management. Agronomy Guide, AY-279. Purdue University Extension Service, West Lafayette, IN. 5 p.

9) Soil Foodweb. 1228 NE 2nd Street. Corvallis, OR.

10) Bollen, Walter B. 1959. Microorganisms and Soil Fertility. Oregon State College. Oregon State Monographs, Studies in Bacteriology, No. 1. 22 p.

11) Jackson, William R. 1993. Organic Soil Conditioning. Jackson Research Center, Evergreen, CO. 957 p.

12) Comis, Don. 1997. Glomalin—soil's superglue. Agricultural Research. USDA–ARS. October. p. 22.

13) Boyle, M., W.T. Frankenberger, Jr., and L.H. Stolzy. 1989. The influence of organic matter on soil aggregation and water infiltration. Journal of Production Agriculture. Vol. 2. p. 209–299.

14) Pipel, N. 1971. Crumb formation. Endeavor. Vol. 30. p. 77–81.

15) Land Stewardship Project. 1998. The Monitoring Toolbox. White Bear Lake, MN. Page number unknown.

16) Allison, F.E. 1968. Soil aggregation—some facts and fallacies as seen by a microbiologist. Soil Science. Vol. 106, No. 2. p. 136–143.

17) Reicosky, D.C., and M.J. Lindstrom. 1995. Impact of fall tillage on short-term carbon dioxide flux. p. 177-187. *In*: R.Lal, J. Kimble, E. Levine, and B.A. Stewards (eds.). Soils and Global Change. Lewis Publisher, Chelsea, MI.

18) Nation, Allan. 1999. Allan's Observations. Stockman Grass Farmer. January. p. 12-14.

19) Sanderson, M.A., et al. 1999. Switchgrass cultivars and germplasm for biomass feedstock production in Texas. Bioresource Technology. Vol. 67, No 3. p. 209–219.

20) Sachs, Paul D. 1999. Edaphos: Dynamics of a Natural Soil System, 2nd edition. The Edaphic Press. Newbury, VT. 197 p.

21) Kinsey's Agricultural Services, 297 County Highway 357, Charleston, MO 63834 573-683-3880

22) Tisdale, S.L., W.L. Nelson, and J.D. Beaton. 1985. Soil Fertility and Fertilizers, 4th Edition. Macmillian Publishing Company, New York. 754 p.

23) Francis, Charles A., Cornelia B. Flora, and Larry D. King. 1990. Sustainable Agriculture in Temperate Zones. John Wiley and Sons, Inc., New York. 487 p.

24) Parker, M.B., G.J. Gasho, and T.P. Gaines. 1983. Chloride toxicity of soybeans grown on Atlantic coast flatwoods soils. Agronomy Journal. Vol. 75. p. 439–443.

25) Schertz. 1985. Field evaluation of the effect of soil erosion on crop productivity. p. 9–17. *In*: Erosion and Soil Productivity. Proceedings of the National Symposium on Erosion and Soil Productivity. American Society of Agricultural Engineers. December 10–11, 1984. New Orleans, LA. ASAE Publication 8-85.

26) Troeh, F.R., J.A Hobbs, and R.L. Donahue. 1991. Soil and Water Conservation. Prentice Hall, Englewood Cliffs, NJ.

27) Sullivan, Preston G. 1998. Early Warning Monitoring Guide for Croplands. Center for Holistic Management, Albuquerque, NM. 22 p.

28) Gantzer, C.J., S.H. Anderson, A.L. Thompson, and J.R. Brown. 1991. Evaluation of soil loss after 100 years of soil and crop management. Agronomy Journal. Vol. 83. p. 74–77.

29) Shiflet, T.N., and G.M. Darby. 1985. Table 3.4: Effect of row and sod crops on runoff and erosion [from G.M. Browning, 1973]. p. 26. *In*: M.E. Heath, R.F. Barnes, and D.S. Metcalfe (eds.). Forages: The Science of Grassland Agriculture, 4th ed. Iowa State University Press, Ames, IA.

30) Jackson, Wes. 1980. New Roots for Agriculture, 1st edition. Friends of the Earth, San Francisco, CA. 150 p.

31) Bowman, Greg. 1994. Why soil health matters. The New Farm. January. p. 10–16.

32) Magdoff, Fred. 1992. Building Soils for Better Crops, 1st ed. University of Nebraska Press, Lincoln, NE. 176 p.

33) Sickman, Tim. 1998. Building soil with residue farming. Tennessee Farmer. August. p. 32, 34.

34) Dirnburger, J.M., and John M. Larose. 1997. No-till saves dairy farm by healing the harm that tillage has done. National Conservation Tillage Digest. Summer. p. 5–8.

Additional Resources

Videos

No-till Vegetables. By Steve Groff. 1997.

This video leads you from selection of the proper cover crop mix to plant into, through how to control cover crops with little or no herbicide,as shown on Steve Groff's Pennsylvania farm. You will see mechanical cover-crop-kill and vegetables being planted right into this mulch using a no-till transplanter. You'll also hear comments from leading researchers in the no-till vegetable area. Order this video for $21.95 + $3.00 shipping from:

Cedar Meadow Farm
679 Hilldale Road
Holtwood, PA 17532
717-284-5152

Books and Periodicals

The Farmer's Earthworm Handbook: Managing Your Underground Money Makers. 1995. By David T. Ernst. Lessiter Publications, Brookfield, WI. 112 p.

To order, send $15.95 + $4.00 shipping and handling to:

Lesiter Publications
245 Regency Court
Brookfield, WI 53045
262-782-4480
800-645-8455

The Soul of Soil: A Guide to Ecological Soil Management, 4th edition. 1995. By Grace Gershuny and Joe Smillie. AgAccess, Davis, CA. 158 p.

To order, send $8.50 + $4.00 shipping and handling to:

Fertile Ground Books
3912 Vale Ave. Oakland, CA 94619
530-297-7879
books@agribooks.com
http://www.agribooks.com/

Neal Kinsey's Hands-On Agronomy. 1993. By Neil Kinsey. Acres, USA. Metairie, LA. 340 p.

To order, send $24.00 + $3.00 shipping and handling to:

ACRES USA
P.O. Box 91299
Austin, TX 78709-1299
800-355-5313 (toll-free)
512-892-4400

Building Soils for Better Crops, 2nd edition. 2000. By Fred Magdoff and Harold van Es. University of Nebraska Press, Lincoln, NE. 240 p.

To order, send $19.95 + $3.95 shipping to:

Sustainable Agriculture Publications
Hills Building, Room 10,
University of Vermont
Burlington, VT 05405-0082
802-656-0484;
sanpubs@uvm.edu.

Edaphos: Dynamics of a Natural Soil System, 2nd edition. 1999. By Paul D Sachs. The Edaphic Press, Newbury, VT. 197 p.

To order, send $14.95 + $1.50 shipping and handling to:

North Country Organics
P.O. Box 372
Bradford, VT 05033
802-222-4277

Soil Quality Test Kit. 1998. USDA. Soil Quality Institute. 82 p.

This publication has detailed, step-by-step instructions with color photographs on how to assess soil quality, soil respiration, soil water infiltration, bulk density, electrical conductivity, soil pH, soil nitrate, soil aggregate stability, slaking, and earthworms. It also covers soil physical observations and estimations and water quality tests, and includes background information on the tests and appendices. To order this free test kit publication, paid for by your federal tax dollars, contact:

Cathy A. Seybold
NRCS Soil Quality Institute
Soil Science Department
Agriculture and Life Sciences Building
Room 3017
Oregon State University
Corvallis, OR 97331-7306
541-737-1786
seyboldc@ucs.orst.edu

or

Lee Norfleet
NRCS Soil Quality Institute
National Soil Dynamics Lab
411 S. Donahue Drive
Auburn, AL 36832
334-844-4741, ext. 176
norfleet@eng.auburn.edu

Early Warning Monitoring for Croplands. 1998. By Preston G. Sullivan. Center for Holistic Management, Albuquerque, NM. 22 p.

To order this guide, send $13.00 ppd. to:

Savory Center for Holistic Management
1010 Tijeras, N.W.
Albuquerque, NM 87102

505-842-5252
http://www.holisticmanagement.org/

LaMotte Soil Handbook. 1994. Lamotte Company. Chestertown, MD. 81 p.

Covers soil basics, nutrients, pH, acidity and alkalinity, and principles of the LaMotte soil testing system. Has relative nutrient and pH requirements for common crops and plants. To order this handbook ask for reference # 1504 and send $4.85 to:

LaMotte Company
P.O. Box 329
Chestertown, MD 21620
410-778-3100
800-344-3100 (toll-free)
410-778-6394 FAX
ese@lamotte.com
http://www.lamotte.com/

How to Get Started in Biological Farming. No date. Gary F. Zimmer. 11 p.

To order this publication, send $3 + $1 shipping to:

Midwestern Bio-Ag
Highway ID, Box 160
Blue Mounds, WI 53517
608-437-4994

Glomalin, a Manageable Soil Glue. 1999. Sara Wright. 1-page brochure.

To order this free publication contact:

Sara Wright
USDA-ARS-SMSL
Bldg. 001, Room 140, BARC-W
10300 Baltimore Avenue
Beltsville, MD 20705-2350
301-504-8156
http://www.ba.ars.usda.gov/sasl/research/glomalin/brochure.pdf

Soil Web Sites

Life in the Soil
http://www.saburchill.com/chapters/chap0059.html

This excellent Web site includes brief overviews of many subjects, including nutrient transformation, biological degradation, soil structure, crop rotation, tillage, soil testing for microbes, and organic matter turnover. Color photos of many soil critters with short descriptions appear on the main Web page. Other drawings and black and white photos of soil microbes and their effects on soil are on other pages at this site.

The Pedosphere and its Dynamics: A Systems Approach to Soil Science
University of Alberta's Soil Science
http://www.pedosphere.com/main.html

A complete on-line soils textbook covering what soil is, ecological functions of soil, soil texture, structure and color, soil formation, Canadian soil classification system, mineralogy, soil reaction, soil water, soil air, soil ecology, soil organic matter, and soil survey. To view this textbook click on the textbook icon at the homepage. Much more information is available from the homepage, including educational resources, tutorials, workshops, publications, etc.

Soil Biological Communities
Idaho state office of the Bureau of Land Management
http://www.blm.gov/nstc/soil/

For drier areas, the Idaho state office of the Bureau of Land Management has an interesting Web site on soil biological communities that covers biological crusts, fungi, bacteria, protozoa, nematodes, arthropods, the soil food web, and mammals. The site has many photographs that bring to life many of the soil inhabitants.

Soil Foodweb Inc.
http://www.soilfoodweb.com/sfi_html/index.html

S. F .I. is the soil microbial analysis lab founded by Dr. Elaine Ingham. In addition to general background on the importance of the soil foodweb, the Web site contains information on commercial products and agricultural practices that support different microbial communities. This site has much interesting information, including how to have soil tested for different soil organisms.

New Generation Cropping Systems
http://www.cedarmeadowfarm.com/about.html

This is the Web site describing Steve Groff's innovative Cedar Meadow Farm in Lancaster County, Pennsylvania. Cedar Meadow is a model sustainable agriculture farm. Steve and his family grow corn, alfalfa, tomatoes, pumpkins, soybeans, small grains, and other vegetables. They use no-till and mechanically killed cover crop mulches in a tight crop rotation. At this Web page you will see action shots of no-till planting into mechanically killed cover crops and find ordering information for Steve Groff's video mentioned above.

Soil Quality Information Sheets
Soil Quality Institute, Natural Resources Conservation Service
http://soils.usda.gov/sqi/soil_quality/what_is/sqiinfo.html

Produced by the Soil Quality Institute, Natural Resources Conservation Service, this Web site features on-line information sheets on soil quality topics. Among the topics are erosion, sedimentation, deposition, compaction, salin ization, soil biodiversity, available water ca pacity, pesticides, indicators for soil quality evaluation, organic matter, soil crusts, aggre gate stability infiltration, and soil pH.

By Preston Sullivan
NCAT Agriculture Specialist

May 2004
IP027
Slot 133
Version 062104

The electronic version of **Sustainable Soil Management** is located at:
HTML
http://www.attra.ncat.org/attra-pub/soilmgmt.html
PDF
http://www.attra.ncat.org/attra-pub/PDF/soilmgmt.pdf